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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Observation of accelerated protons during the injection of rotating relativistic electron beams into neutral hydrogen (50 mTorr to 400 mTorr) indicated that ions from the beam-formed plasma are trapped and accelerated by a potential well at the beamfront. Measurements show that the number of accelerated protons decreases as the beamfront velocity is increased. Moreover, at a given velocity, the number accelerated is relatively insensitive to the neutral gas pressure.

COLLECTIVE ACCELERATION WITH ROTATING RELATIVISTIC ELECTRON BEAMS

Collectively accelerated ions have been observed in a number of experiments[1] where relativistic electron beams were injected into neutral gas filled drift tubes. This paper presents results of recent experiments in which up to 10^{14} protons are accelerated when a rotating beam is injected into neutral hydrogen in the absence of an applied magnetic field. An acceleration mechanism consistent with these observations was first proposed by Rostoker[2] and later developed in detail by Olson[3]. It involves the trapping and subsequent acceleration of ions from the beam-formed plasma by the potential well associated with the electron beam. The well is produced because the beam cannot generate sufficiently dense plasma on a fast enough time scale to fully charge neutralize the beam head.

To accelerate large numbers of ions (10^{13} to 10^{14}), the potential well at the beamfront must be deep enough and accelerate slowly[4] enough to overcome ions' inertia. In this experiment, the large number of accelerated protons appears to be due to the relatively slow axial velocity, v_b, of the rotating beam. This slow velocity arises because the need to supply the self-fields limits the propagation speed in accordance with the predictions of a simple model.[5] Effectively, the beam is retarded by the inductive load of the self-field configuration similar to the manner in which current is impeded from being driven in a coil. By changing the neutral gas pressure, diode impedance or beam rotation parameters, v_b can be varied in a controlled manner to velocities as low as 0.03 c.

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Collective acceleration experiments of this type have all used non-rotating beams, with the exception of the experiments of Roberson,[6] et al., in which up to 10^{13} protons per pulse were reported. In that study, however, a magnetic field was applied in the drift tube. Rander[7] has measured the beamfront velocity, ion yield and ion momentum distribution for non-rotating beams in hydrogen. In the experiments reported here, comparable results are presented for rotating beams. Moreover, this is believed to be the first experiment in which the number of accelerated ions is correlated with the velocity of the electron beam over a broad range of parameters, and in which v_b is varied in a controlled fashion.

A schematic of the experimental apparatus is shown in Fig. 1. The rotating relativistic electron beam is generated by injecting a hollow beam ($\nu/\gamma \sim 2.0$) from an annular carbon cathode (6.0 cm I.D., 6.5 cm O.D.) through a half-cusp magnetic field configuration. This configuration is produced by a solenoid around the cathode region and a 2.5 cm-thick aluminum plate located 2 mm beyond the aluminized Mylar anode foil. A ferrite core inside the cathode constrains the field lines to emanate perpendicular to the emission surface; however, they are diverted radially outward by currents induced in the aluminum plate during the 400 μsec rise of the solenoid field. This produces an axial magnetic field, B_0, near the anode which goes from 90% to 10% of its strength in a distance of 2 cm. The electron beam acquires angular momentum as the axial velocity of the beam interacts with the radial component of the half-cusp field, and the resulting rotating beam (radius $r_b = 3.2$ cm) enters the 50 cm-long stainless steel drift tube (radius $R = 7.3$ cm) with both axial and azimuthal velocity components. Radial equilibrium for the injected beam is provided by the self-magnetic fields (axial and azimuthal) and currents induced in the drift tube wall.[8] Diode voltage and current are $V \sim 900$ kV, $I \sim 80$ kA for $\tau \sim 100$ ns, with voltage and current rise times of about 20 ns.

The number of accelerated protons, N_p, is inferred from the activation of thick carbon targets through the $^{12}C(p, \gamma)^{13}N(\beta+)^{13}C$ reaction[9] and is shown as a function of target axial position in Fig. 2. Protons with energies greater than 457 keV are recorded by this technique. By varying the target position over the length of the drift tube, N_p increases rapidly from less that 10^{10} to approximately 10^{14} in the first 15 cm. The number of protons then remains constant for at least 35 cm, indicating that the acceleration occurs in the first 15 cm of the drift tube. The lack of accelerated protons detected near the anode foil also indicates that the protons are not being produced in the diode, but are generated in the beam-formed plasma. Measurements show that roughly 10% of the protons are lost radially to the drift tube wall and suggest that they tend to remain localized in the beam channel. Observations of annular beam and plasma profiles with witness plates and framing photography preclude the possibility of a pinched-beam process[10] as an accelerating mechanism.

Proton energy distributions are determined by placing thin aluminum absorbers in front of the carbon targets, using published[11] energy loss data. The proton energies are resolved into bins 300 ± 30 keV wide by using absorbers from 1.3 mg/cm^2 to 6.7 mg/cm^2 thick. Figure 2 is a reconstruction of the proton energy distribution for an average beamfront velocity of v_b = (0.042 ± 0.007)c. The location of the peak in Fig. 3 suggests a mean proton velocity of v_p = (0.044 ± 0.005)c. This matches the beamfront velocity to within experimental accuracy. Similar velocity matching is observed for other values of v_b, indicating that the protons are accelerated in a compact bunch and acquire the velocity of the moving beamfront. This is a common feature of collective acceleration experiments[12] using non-rotating beams.

Average values of N_p are shown against H_2 fill pressure in Fig. 4-a. The beamfront velocity is determined from the difference in time of arrival of the signals from magnetic probes

located 15 cm and 45 cm from the cusp. Average values of the beamfront velocity are also shown against fill pressure in Fig. 4-b. At fill pressures below 50 mT, the beam propagation is probably dominated by electrostatic processes. The plasma density is insufficient to reduce the potential at the beamfront to below the electron beam energy, which results in the formation of a virtual cathode that prevents an appreciable fraction of the beam from propagating. Significant loss of current with distance is observed, with the current 45 cm from the cusp less than 10% of that at 15 cm from the cusp. At the higher fill pressures, sufficient plasma is created and the electrostatic effects no longer dominate; the beam motion is then governed by magnetic forces.[5] As the pressure is raised, v_b increases because the increasing plasma density allows the beam current to be partially neutralized and thus lowers the magnetic energy that must be supplied by the beam. This increase in v_b might be responsible for the decrease in N_p at fill pressures above 75 mTorr. Raising the pressure, however, may limit the number of accelerated protons by reducing the depth of the well. The role of the beam velocity is determined by varying v_b independent of the pressure. Results shown in Fig. 4 are obtained by varying the pressure and this data is represented by the circles in Fig. 5. At a given pressure the beamfront velocity can be increased by reducing the magnitude of the half-cusp field.[5] The triangles in Fig. 5 represent these results. The effect of the half-cusp field on the beamfront velocity is summarized in Table 1 along with a comparison of beamfront velocities and the number of accelerated protons for various pressures. Total injected current is held constant. The number of protons decreases by about an order of magnitude as the beamfront velocity increases by about a factor of 2. Moreover, for a given beamfront velocity, an increase in the pressure by a factor of 2 has negligible effect on N_p. Note that the fall-off in N_p at beam velocities below 0.031 c (or pressures below 75 mTorr) may be an artifact of the diagnostic: The minimum energy required for target activation corresponds to protons with velocities of 0.031 c.

Accelerated deuterons present in isotopic abundance will also contribute to the apparent value of N_p through the $^{12}C(d,n)^{13}\ N(\beta+)^{13}C$ reaction.[13] Corrections for deuterons having velocities comparable to v_b will steepen the fall-off of N_p with increasing v_b by about an order of magnitude, without affecting the maximum value of N_p (Fig. 4-a and Fig. 5).

The data presented indicates that protons from the beam-formed plasma are trapped and accelerated by potential well at the beamfront and that the acceleration occurs in the first 15 cm of the drift tube. Mean proton velocities are equal to the axial velocity of the rotating beam to within experimental accuracy. The number of accelerated protons decreases as the beamfront velocity is increased, and we believe that the relatively large number of accelerated protons observed in this experiment is due primarily to the slow axial velocity of the rotating beam.

If the protons are indeed trapped in a potential well, the velocity of the beamfront can, in principle, be increased after the well is loaded in order to attain higher proton energies. One way to achieve this is by decreasing, with axial distance, the inductive loading on the beam due to the self-magnetic field configuration. This concept has been discussed elsewhere,[14] and experiments to test this concept are underway.

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Table 1 — Comparison of beamfront velocities and the number accelerated protons for various pressures and values of B_0.

PRESSURE (mTorr)	B_o (kGauss)	v_b ($\times 0.01c$)	N_p ($\times 10^{13}$)
50	0.3	6.8	1.82
200	4.5	6.9	1.80
100	0.5	8.3	0.73
300	4.5	8.5	0.70
200	0.5	10.0	0.24
400	4.5	9.6	0.23

Typ. $v_b \pm 0.007c$; $N_p \pm 2.6\times 10^{13}$

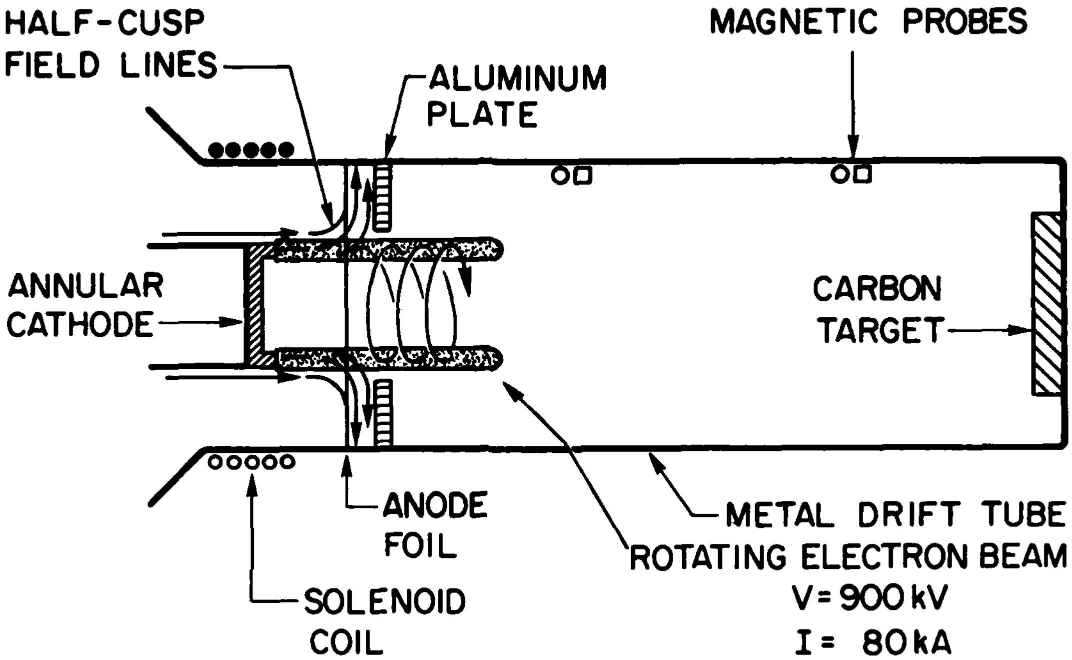

Figure 1 — The experimental facility. The position of the carbon target can be varied from 2 to 50 cm.

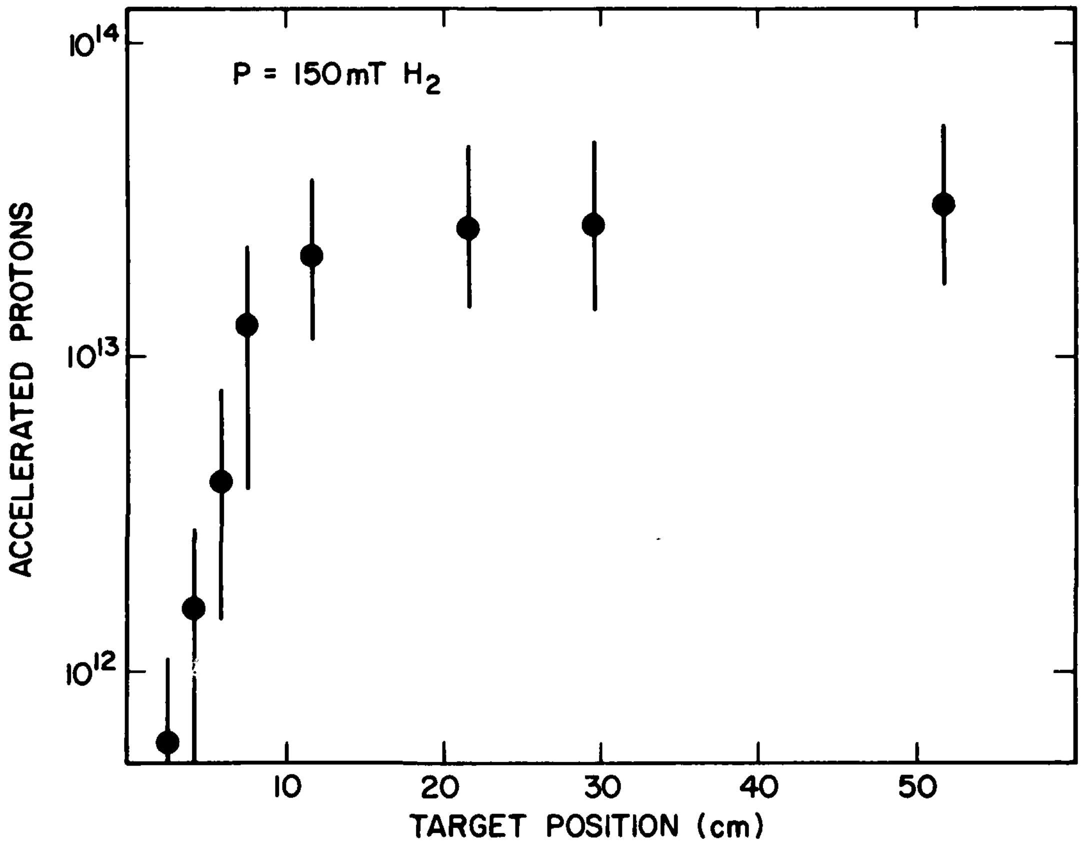

Figure 2 — Number of accelerated protons as a function of target axial position.

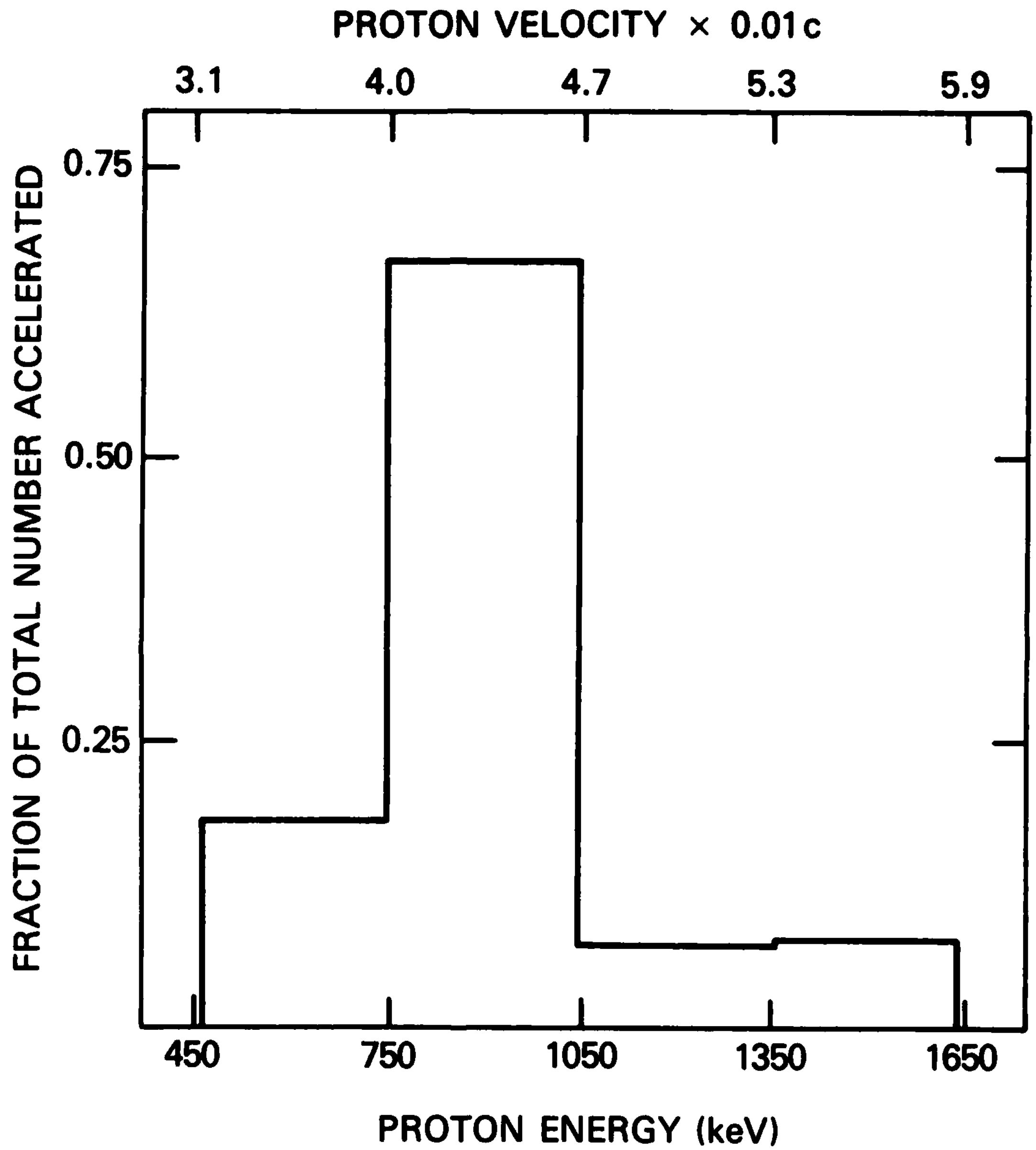

Figure 3 — Proton energy distribution for an injected beamfront velocity of v_b = (0.042 ± 0.007)c.

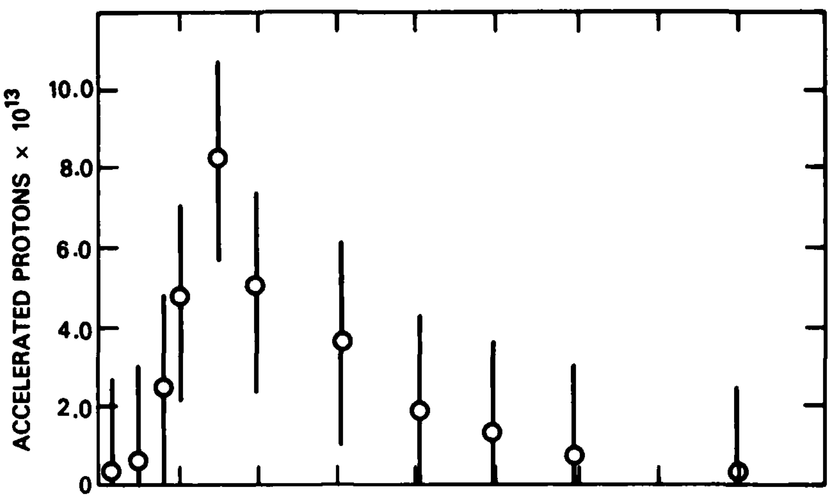

Figure 4a — Average number of accelerated protons as a function of H_2 fill pressure.

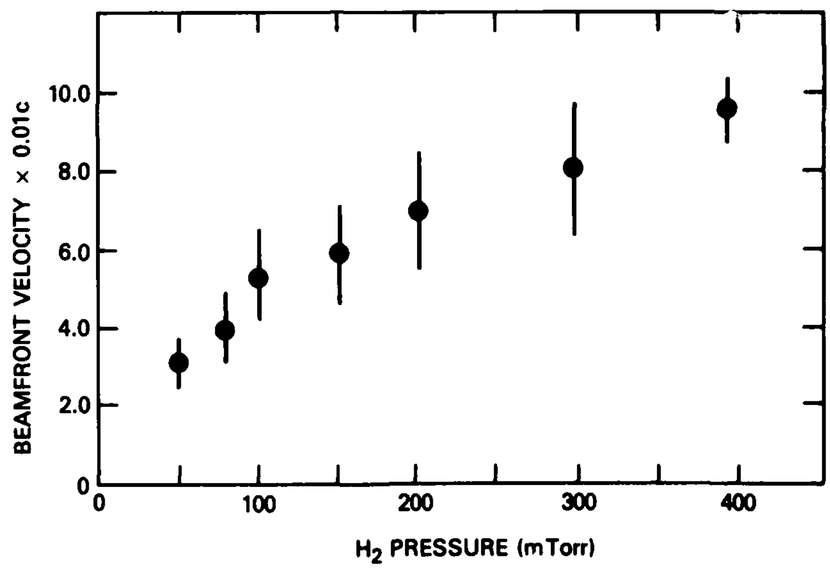

Figure 4b — Beamfront velocity, measured by magnetic probes, shown as a function H_2 fill pressure.

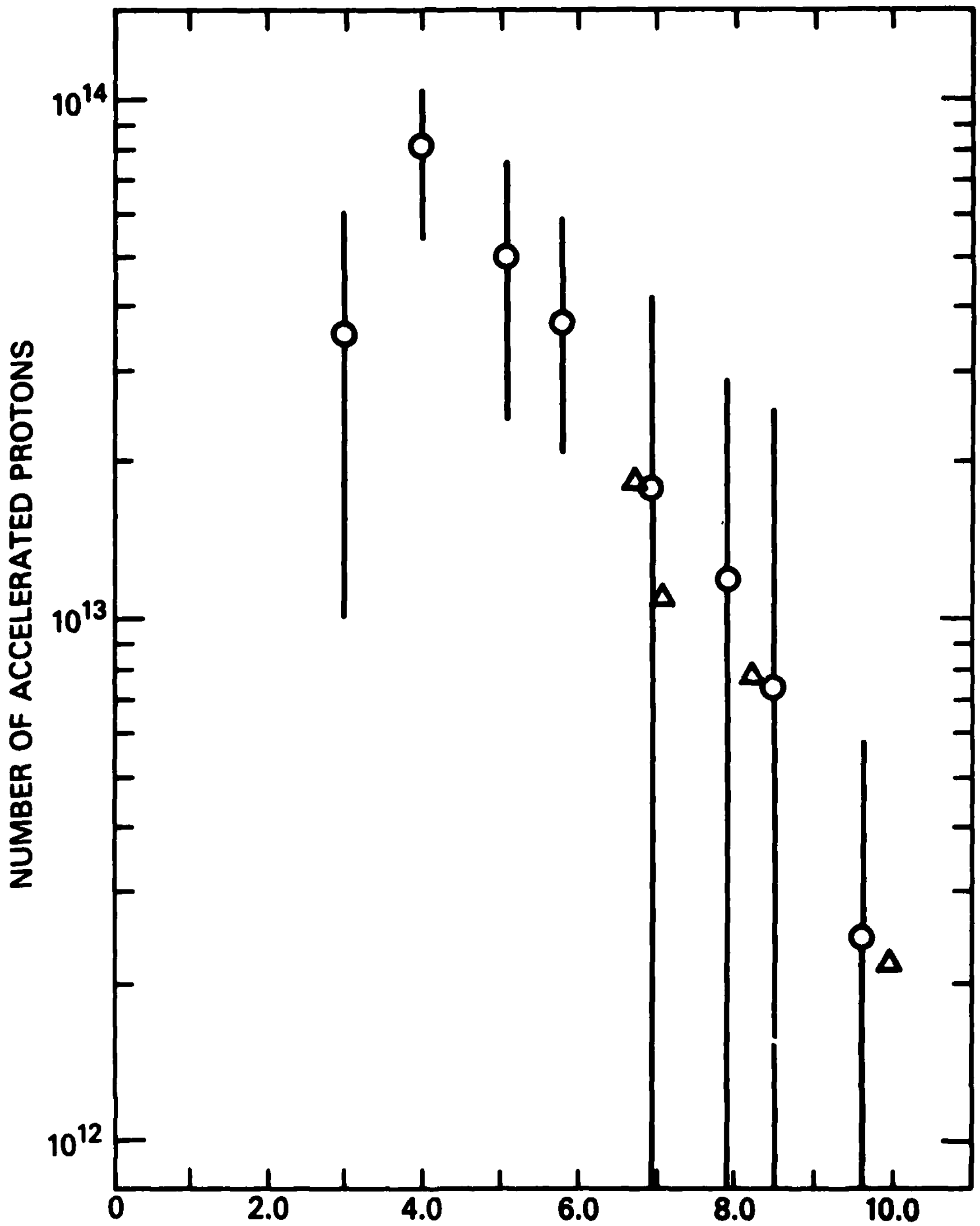

Figure 5 — Number of protons accelerated as a function of beamfront velocity. Results for $B_0 = 4.5$ kGauss are represented by circles (average values). The triangles represent results for $B_0 \leq 1$ kGauss (single shots).